FROM AEROSPACE PHOTOGRAPHS TO FORECASTING AND CALCULATING FLOWS

G. P. Kalinin

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16. Abstract

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Methods of calculating flow and the characteristics of the snow cover are suggested based on photographs that characterize the dynamics of the hydrological processes that occur on the surfaces of river basins.

Problems of experimental investigations leading to new possibilities of analysis and calculation of a number of hydrological elements are posed.

The book is intended for hydrological specialists.

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ANNOTATION

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G. P. Kalinin

INTRODUCTION /3*

The prospects for the development of hydrology with respect to man's entry into estraterrestrial space are determined by the developmental level of this science, and by its capacity to pose and solve new problems, most effectively using modern and forecasting capacities of a new system of studying nature. The following most important problems of hydrology have now appeared:

1) Isolating processes of evolution of natural waters that have led to their present condition both on the Earth and in space:

2) The development of new methods of studying the dynamics of surface, soil, and subsoil waters in different phase states.

The pressing nature of the first problem is apparent from the particular position occupied by the aqueous envelope on the Earth, as opposed to the other planets, which in the final analysis is one of the important conditions for the development of life. Establishing the reasons that determine the relationship between the moisture that emerges on the surface of a planet from its depths and that which it loses into space is a basic problem.

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* Numbers in margin indicate pagination in original foreign text.

The complexity of solving this problem consists not only in the fact that differences in masses of planets and their distance from the Sun has an effect, but also in the extremely slight process of influx of water to the surface of the Earth and the water balance with space which is difficult even to approximately estimate.

It is extremely probable that the appearance of water first on a small part of the Earth's surface, created in some period of terrestrial development, made possible the development of the biosphere. As opposed to the other planets, the appearance of the biosphere led to the transformation of the gaseous composition of the Earth's atmosphere, and to the formation of a "screen" that slowed the loss of water into space and created conditions for its replenishment on the Earth's surface.

The stratospheric water vapor trap (linked with the presence of ozone in the stratosphere) that was created in the process of terrestrial evolution, thereby preventing the diffusion of water vapor upward, is an extremely fine mechanism which appears in a very limited range of physical conditions, since it functions in this form only on the Earth, of all the other planets of the solar system. The pressing nature of studying this mechanism is /4
enhanced by the fact that with intensive human intervention in nature, it is possible that conditions could appear leading to its disruption.

Obtaining new data on the distribution of water and on the factors of its formation in space and on the planets, and a study of their aqueous cycle will permit a solution of this problem.

With respect to the second problem, there are a number of branches of hydrological science that are concerned with the development of remote methods of investigation. They specifically include the following:

1) Calculations and predictions of flow formation;
2) Contamination of reservoirs;
3) Thermal aspects of reservoirs and the ice cap;
4) The dynamics of the snow cover and glaciers;
5) Moisture reserves of the atmosphere and soil;
6) Levels of subterranean waters, the entry of subterranean waters into lakes, seas and oceans;
7) The erosion of soil and banks, the structure of modern and ancient river networks, etc.

Even this incomplete list indicates the great interest in remote methods of investigation. However, most studies devoted to these types of investigations are basically of a partial character or only fix the characteristics of a single phenomenon in photographs. With respect to this, theoretical analysis and practical use of new information far from corresponds to available capacities. Today, there are numerous general discussions on the use of remote methods. However, in their practical application there are significantly fewer successes than one should expect. Therefore, having already given credit to general discussions in the introduction, we shall subsequently concentrate our attention on developing specific methods of using remote observations in a field more familiar to the author — the method of forecasting and calculating flow.

Presently there are capacities for creating a new and more accurate system of predicting hydrological processes that is based both on the logic of hydrological development, on new methods of obtaining information, and on new types of information. In order more convincingly to illustrate the practical reality of the suggestions advanced, the author deliberately avoids disputed questions, inasmuch as possible at least, and makes maximum use of the calculation components of those methods of prediction, that have already passed many years of testing, as the component elements.

The more intensively any branch of science dealing with nature develops, the greater are the requirements it makes on setting up new observations and increasing their accuracy. Therefore, it is entirely in keeping with this principle that in this study many requirements are given for setting up new experimental studies and observations.

The basic concepts of this study are the following:

1. Although the objects of hydrological investigations are essentially processes of formation of water on the surface of the Earth, the main source of information was only observations of weather stations, and due to the limited territory covered by these stations, they cannot provide adequately complete concepts of the dynamics of the processes studied. Direct observations of the dynamics of hydrological processes over territories of various sizes could significantly improve, the study of the examined processes and the accuracy of their calculations.

2. The widely accepted theory for the formation of flow, in combination with certain empirical data, makes it possible to obtain transition functions from the weather station observations to the flow, according to the materials of observations. The so-called genetic flow formula is of such a general character that in principle (with a certain modification) it can also be applied to the new information obtained from photographs.

This makes it possible to use the already known apparatus widely for solving a large range of hydrological problems, using the qualitatively new information.

3. The relationship of the flood plain (surface of the basin, gulley-marsh area in the river network), the extent of the network of water flows with the hydraulic characteristics of these elements of the terrain, and the flow of water, is near a functional relationship. Although the structure of these relationships has not yet been fully revealed, one can principally establish them by analyzing the observation materials, using the extensive experience of solving the opposite problems.

4. The different dimensions of the mentioned characteristics of surface coverage of drainage collecting systems, and also of the gulley-marsh and river network make it possible to use any initial observation material in the calculations, depending on the resolving capacity of the apparatus. This gives great flexibility to the possibilities of using photographs under conditions in which a system of forecast and predictions will be developed, permitting the use of any of the variously scaled images of the surface as a basis.

5. In the final analysis, the flow from a basin surface is the difference between precipitation and flow losses. These elements, specifically flow loss, are determined extremely roughly for a number of known reasons, which leads to large errors in forecasts and calculations. Moreover, the area of water surface coverage of a basin can be represented as a consequence of transformation of the mentioned difference in precipitation and flow. This creates the prerequisites for using more direct flow factors as original data, so as to avoid such gross characteristics in forecasts and calculations. Specifically, the uniqueness of such a characteristic as the basin surface coverage area should be emphasized; this is simultaneously an index of feed-in of surface and subterranean waters.

6. The presented material creates the possibility /6
of restructuring the modern system of forecasting and calculations to another system logically connected with it, but one which uses new information.

7. The great significance of the new capacities of forecasting will stimulate the development of new experimental investigations of the surfaces of basins, the structure of the water conducting network, the complex of hydrological processes, and the events going on within them. A particular role here is recognizably played by experimental testing grounds, which should provide for terrestrial observations, observations from stationary towers (photographs, terrestrial radio-activity, surveys, etc.) as well as observations from high altitude aircraft and satellites.

THE METHODOLOGICAL FOUNDATIONS OF FORECASTING FLOW USING AEROSPACE PHOTOGRAPHS OF FLOOD PLAINS OF A BASIN SURFACE AND CHANNEL NETWORK

The characteristics of processes that occur on a basin /7 surface (specifically, the areas occupied by the water surface) are most easily determined by remote data.

On the other hand, there is a nearly identical relationship between the areas of flooding and the subsequent flow through the last section of the river.

Hence, the problem of investigating forecasts and calculations of flow using remote sensing methods is the following:

a) Establishing direct relationships between covering areas of the examined elements of the basin by the water surface, and the characteristics of flow.

b) Establishing the characteristic area coverage dimensions by water under any particular hydrological condition;

c) Determining the accuracy of measuring these areas or their integral characteristics by remote methods today, and in perspective, in accordance with the resolving capacity of the apparatus.

The first two problems entirely pertain to the field of hydrological investigations. In the last one, the role of hydrology pertains to establishing requirements for the remote investigations for solving hydrological problems with the necessary degree of accuracy.

As will be shown below, the varied processes in formation of flow and the strict sequence of their development in time create extremely favorable prerequisites for broadly employing remote methods.

Actually, in the first phase of flow formation, following the movement of the water to the surface of the basin, the lower and low-filtering parts of the basin immediately fill, i.e., a network of flowing and nonflowing microlakes forms on the surface of the basin. The curve of distribution of areas F of nonflowing and flowing microlakes is a function of the reserves of water on the surface of basin or the sloping flow that changes little with time. The total area covered by water can be represented as $F_{tot} = f(W)$ or $F_{tot} = \psi(q\ slo)$. /8

The dimensions and areas of individual microlakes depend on the constant physico-geographic conditions (primarily inclination) and the conditions of flow formation that are variable in time. The smaller the dimensions of the microlakes, the greater these are. The range of fluctuations in dimensions of microlakes is very great; from fractions of square meters to hundreds of square meters or even several square kilometers. During large floods, the dimensions of microlakes increase.

The areas of basin surface coverage by microlakes, measured remotely, characterize the following:

a) The basins total area of microlakes whose dimensions exceed the resolving capacity of the apparatus;

b) Changes in the reflecting capacity as the result of changes in the total area of the mirror of the microlake water.

For developing a method of solving these problems, it is necessary to combine terrestrial and remote observations. We specifically note that, since filling of microlakes occurs synchronously and depends on the same causes, there should be an intimate relationship between the total area of the basin covered by the water and the area of the largest floods. Such a relationship is of course unique for each basin.

It should be noted that the smaller the inclines of the basin and the larger the flow rate, the greater will be the dimensions of the basin area covered by water. Thence, it follows that the most favorable conditions for predicting flow with such an approach are available for large floods of plain basins.

One of the basic complexities in determining the change in time of basin water coverage area is the short duration of this process, which is frequently measured in hours or days, and which requires an appropriate frequency of measurements.

With a natural resource measurement frequency of about 2 times per month from satellites, one cannot trace the dynamics of water collector surface area coverage by water. The data of the satellites can be used for estimating the dynamics of soil moisture, which change significantly more slowly. For solving many of the hydrological problems, the frequency of making satellite measurements in individual phases of the hydrological regime should be the same as that from the weather satellite, but in certain cases it should also be greater.

The second phase in flow formation consists in the influx of water into depressions and dry valleys.

In the period of flooding in dry valleys, quite significant water flows form, since the reservoir area of dry valleys usually comprises 5-10 km^2 with very rough terrain, and up to 20-25 km^2 with a slightly rough relief. Here, the process of flow formation is more prolonged than that from slopes.

It should be noted that the transition from one flow phase to another extends over a certain period of time.

The next phase is a gradual formation of the flow of rivers of the first, second, or higher orders. A number of studies have been devoted to investigating the structure of a river network — R. Horton [33], N. A. Rzhanitsyn [36], L. D. Kurdyumov [29], R. A. Nezhikhovskiy [21] and others.

In agreement with R. Horton, we shall consider the smallest 79
water flow that is not a tributary to be a river of the first order, and the flow formed as the result as merger of two first order rivers — a river of the second order, etc.

R. Horton established the following principles [33]:

$$N_\theta = E_N^{\varphi-\theta} \quad \text{and} \quad \bar{L}_\theta = \bar{L}_1 E_L^{\theta-1},$$

Where N_θ — number of tributaries of the θ-th order in a given basin; φ — order of main river; E_N — a parameter that changes from 2 in flat regions to 4 in mountainous regions; $\bar{L}_\theta$ — mean length of tributaries of a given order; $\bar{L}_1$ — a parameter; E_L — a parameter with a mean value of 2-3.

N. A. Rzhanitsyn [27] also obtained relationships that permit one to determine the area and length of rivers.

It is necessary to emphasize the value of map scale. Thus, water flows that are of the first order on a map having a scale 1:10,000,000 are of the 3rd - 4th order on a map having a scale of 1:100,000. The mean length of a first order tributary for the

European part of the USSR is 5 km on the 1:1,000,000 map, and 0.6 km on the 1:25,000 map.

The distribution of rivers of different orders has common aspects for different territories.

Depending on the resolving capacity of remote measurements used as initial elements for which the mirror area of a river is determined, one should choose rivers of any order, and consequently, those that differ in their indices and dimensions of the surface flow characteristics. Actually, as was mentioned above, one can take either the flood area of the basin surface with dimensions of microlakes that exceed the resolving capacity of the apparatus for characteristics of the slope flow, or the reflecting capacity of the entire basin surface with coverage of the basin surface by small microlakes. Filling of the gulley-marshy area and channel network is characterized by the area of channel and flood plain floodings.

It should be borne in mind that interpreting satellite photographs is already successfully done for obtaining morphometric characteristics and estimates of river regimes. The standard interpretation of satellite photographs conducted for a number of regions shows that they practically reflect all river and lake networks [7]. Here, the good overview of photographs makes it possible to study the structure of the network as a whole.

In these photographs, permanent rivers show through even with slight river size (less than 10 km), and the channel is clearly depicted in all details. In the satellite photographs, one can reliably recognize temporary water flows that have the appearance of light-gray, extended, occasionally convoluted bands. The boundaries of river flood plains show through in significantly more detail than on large scale maps; these are noted by their generally darkened tone. Therefore, (particularly during catastrophic floods characterized by large overflows), satellite and aerial photographs can make it possible to attain quite high accuracy in forecasts. /10

DETERMINING AND FORECASTING SURFACE FLOW ACCORDING TO THE AREA OF WATER COVERAGE OF THE BASIN SURFACE

A nearly functional relationship exists between the surface flow of water into a river network q and the amount of water W located on the surface of a basin

$$q = f(W). \tag{1}$$

On the other hand, there is also a nearly functional relationship between the area of water surface coverage of a basin ω and W

$$W = \varphi(\omega). \tag{2}$$

Thus

$$q = \psi(\omega). \tag{3}$$

Hence, for determining the inflow of surface waters into a river network, two problems should be solved: finding the proportion of area of a basin covered with water and discovering the relationship between this value and the influx of water into the river network.

The first part of the problem is solved by aerospace methods or by directly determining the area covered with water or according to the mean reflecting capacity of the basin surface. In the latter case, one uses the preliminary established relationships between these changes and the degree of coverage of the basin surface by water.

Determining and forecasting the surface flow according to the areas covered with soil having differing degrees of moisture content is extremely promising, or can be extremely promising for future investigations. Today, methods of determining reserves of water in the upper layer of the soil by the aid of aerial gamma-photography have already been developed [24, 32].

Judgments on the soil moisture can also be made according to satellite images in the visible range, and for studying the regional moisture field; even comparatively low spatial resolutions that are provided by the scanning element of television images on the order of 1 km are adequate. It has been shown in a study [6] that there is an extremely good correlation between the albedo of soils with varying moisture content and the density of the negative image, which makes it possible to determine soil moisture according to the intensity of the television image signal.

Examples of verifying the outlines of precipitation and boundaries of soil moistening according to color photographs obtained from the "Gemini-4" spacecraft [6] are reliable for studying rainfall floods according to satellite data. /11

New capacities for determining the quantitative characteristics of soil moisture are revealed when using methods of passive radar in the centimeter band. According to the studies [4, 5, 9], a linear decrease in the radio brightness temperature with an increase in soil moisture was established according to the data of measurements of the microwave radiation at wavelengths of 3.4 and 8.5 cm. Subsequently, a number of studies appeared [9, 16, 17], in which attempts are made quantitatively to determine moisture by solving inverse problems of finding the physical parameters of the soil according to the field of its thermal radiation.

Greatest interest for hydrological forecasting is estimating the distribution of the amount of water in the soil, by depth, according to the data of measuring the radio brightness temperatures at wavelengths of 0.81; 2.2; 6.0 and 21.4 cm [42].

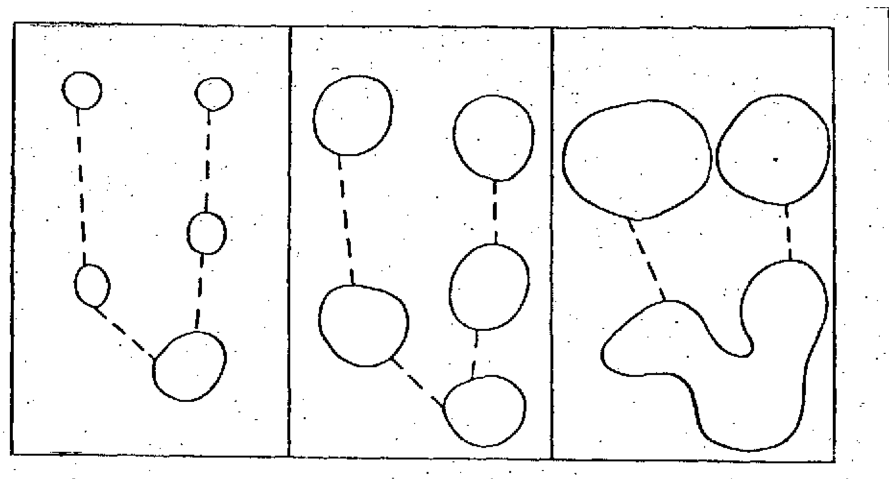

Figure 1. Diagram in the change of basin water cover with an increase in the flow rate.

The second part of the problem can be solved in two ways or by a combination: the first of these consists in a theoretical-experimental foundation for the form of the relationship $q = \psi(\omega)$, and the second is based on solving an inverse problem — according to observations of ω and q, one establishes $\omega(q)$. For solving the problem in the first way, it would seem one could use theoretical constructions for calculations of the slope flow; however, in an overwhelming majority of cases these are based on a conception of a dense slope flow. Such an approach is useful for certain calculation systems, but in this case it is entirely inapplicable, since a solution in the examined method is in fact based on the conditions of an incomplete water basin cover that exist in nature (Figure 1). Therefore, the development of a theory that takes into account the nondensity of formation of the surface flow and an experimental study of the structure of the basin surface and the related flow conditions is important. Here, it is primarily important to clarify the form of relationship $q = \varphi(\omega)$, and it is also important to establish the distribution curve of the volume of the nonflow depression, which is one of the important aspects in the theoretical formulation. We shall examine the latter first. /12

If one imagines a slope with an incline i, on which there are a number of depressions limiting the flow (Figure 2), then the volume of the depressions per unit width of the slope (with a large flow), or the volume per unit width of the microlakes (with a small flow) will be

$$W = \frac{H^2}{2i}; \tag{4}$$

From (4) we have

$$H = \sqrt{2iW}. \tag{5}$$

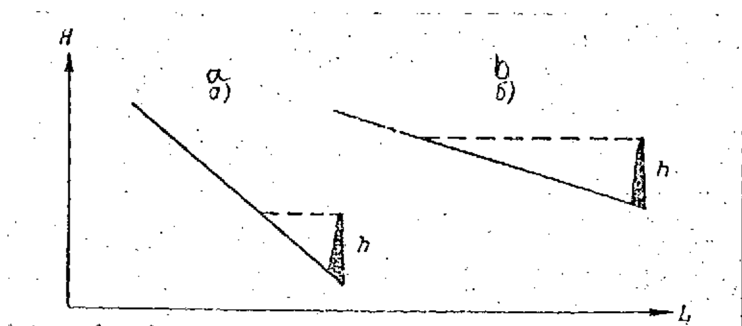

Figure 2. Diagram illustrating the change in water volumes on the surface of a basin as a function of the incline at constant dept.

a- large incline; b- small incline.

If the distribution curve f(H) is known, then the curve of volume distribution φ(W) corresponding to it is expressed by the relationship

$$\varphi(W)=\frac{i}{H}f(H). \qquad (6)$$

Thence, one can see that even with a curve near the symmetrical normal curve for distribution of a layer of water f(H), the curve of volume distribution φ(w) is sharply asymmetrical. On the other hand, it is clear that, all other conditions being equal, the area occupied by water will be the greater, the lesser the incline. One can assume that in a number of cases the principles noted above will also be justified to a certain extent for volumes of water during overflow through individual highlands, since the layer of overflow water can be significantly less than H. With respect to the distribution curve of areas ω, in character these are similar to the distribution curves H, since the area per unit width is

$$\omega=\frac{H}{i}. \qquad (7)$$

The total inflow of water to the river network can be approximately expressed by the relationship

$$q=CS\overline{H}^{1+2/3}i^{0.5}, \qquad (8)$$

where C — a parameter that depends on the roughness of the slope; $\overline{H}$ — mean depth of flow near the channel network; S — length of slope along the shoreline.

Based on the data of L. G. Abramov [1], an attempt was made in [13] to establish the relationship between q and W. For this purpose, in the case of constant intensity of precipitation $\overline{Ix}$, water absorption was calculated according to the formula of G. A. Alekseyev [2]

$$V_x=k+\frac{A}{\sqrt{t}}. \qquad (9)$$

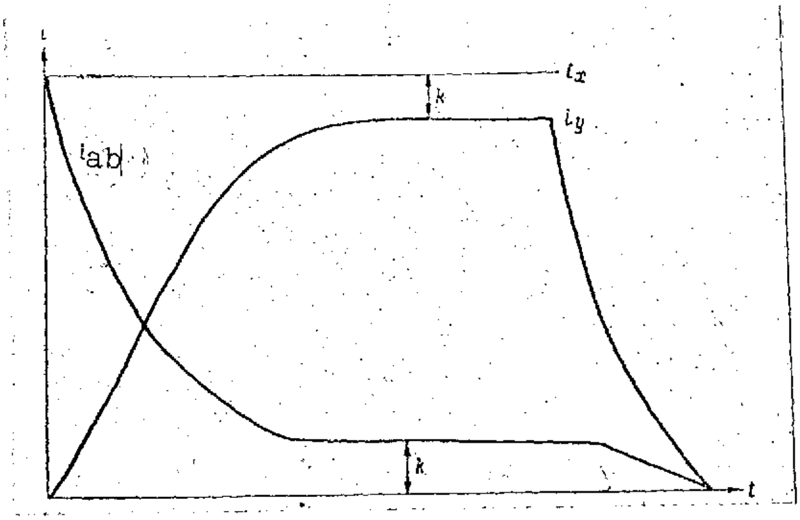

Figure 3. Time change in the intensity of precipitation (i_x), intensity of flow (i_y) and intensity of absorption (i_{ab}).

Parameter k is established according to the absorption rate during a long rain, when stabilization of the water outflow has already been established (Figure 3).

Parameter At_{max} is determined from the condition

$$\int_{t}^{t_{max}} q\,dt = \int_{0}^{t_{max}} (i_x - V_x)\,dt = \int_{0}^{t_{max}} \left(i_x - \frac{A}{\sqrt{t}} - k\right) dt, \tag{10}$$

where t_{max} — time from beginning of rainfall to end of flooding.

The value of running volumes of water W_t on the surface of an inclined plane, after establishing parameters A and k, was determined according to the relationship /14

$$W_t = \int_{0}^{t} \left(i_x - y - \frac{A}{\sqrt{t}} - k\right) dt, \tag{11}$$

where y — flow per unit time, W_t — volume of water per unit area.

A comparison of the volumes obtained when they are averaged over time of flow τ from the upper parts of the slope to the overflow trough showed the presence of a close linear relationship between q and $\bar{W}$ (Figure 4). The expediency of introducing the average ($\bar{W}_\tau$) is entirely understandable, since the water flow rate, according to the genetic flow formula, consists of volumes of water that have entered the surface of the basin at different periods of time, which is more accurately reflected by the equation

$$q = \int_0^{\tau_{max}} f(\tau)\,\varphi(W_{t-\tau})\,dt, \tag{12}$$

where f(τ)— function of effect (lag curve).

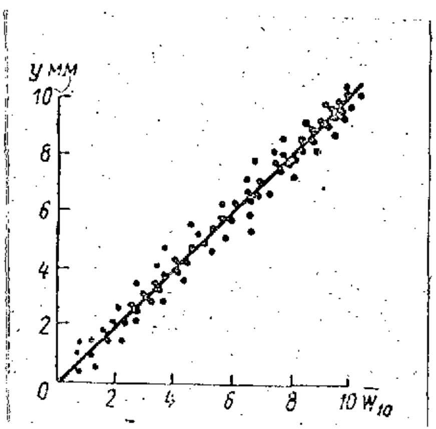

Figure 4. Relationship of a flow layer to volumes of water averaged over ten-minute time intervals.

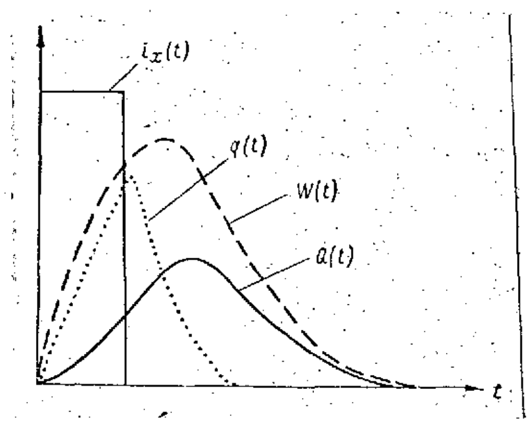

Figure 5. Sequence of time behavior of precipitation rate (i_x), inflow of water q(t), volumes of water W(t), and amount of water flow through a closed section Q(t).

This also follows from the known time sequence of precipitation onset x, inflow q, volume of water W, and flow Q (Figure 5).

Actually, even a small area is an enormous series of micro-basins with a certain accumulated volume that creates the basic mass of water volumes formulating the flow to the runoff trough. Here we have a process on a microscale similar to that which subsequently occurs throughout the river network. The nearly linear relationship between the volumes of water on the slope and passage of water from the slope is probably significantly determined by the similar exponents in formulas (4 and 8). Since the relationship between volumes of water and areas of basin water cover is nonlinear, the relationship of inflow of water and area basin coverage will probably have the form /15

$$q = A\omega^n, \tag{13}$$

where n > 1.

We must now resort to certain hypothetical conclusions because, notwithstanding the immense importance of reports concerning areas of water coverage and volumes of water for the practice and development of the theory of flow formation, at present there actually are no data of these observations. It is necessary to carry out a series of experiments in the field, using the available flow areas, that would permit one to cast light on these important aspects of flow processes. In addition to the terrestrial measurements, an important role here should also be played by systematic high altitude photography of flow formation in the elementary basins. Until the accumulation of these data, we had to limit ourselves to certain approximate solutions. As the experience of hydrological forecasts has shown, the most effective results could be obtained by solving the inverse problems. In the case of interest to us, these problems are the following:

a) Determining the influx of water into the river network according to the area of basin surface coverage;

b) Determining the lag curve and flow in the closed section according to the calculated influx. Using the existing concepts on the conditions of flow formation, data on the areas of basin coverage and flow, and the experience accumulated in hydrological forecasts, one can solve these problems.

Actually, let us assume we have a series of observations on the dynamics of areas of water cover, and a series of corresponding data on the flow of floods. We assume that the relationship between q and ω can be expressed by such formulas as:

$$q = A\omega^n,$$

or

$$q = a\omega + b\omega^2. \tag{14}$$

We use the obvious condition that

$$\sum q = \sum Q, \tag{15}$$

where Q — daily flows of water, then

$$A \sum \omega_i^n = \sum Q_i, \tag{16}$$

or

$$a \sum \omega_i + b \sum \omega_i^2 = \sum Q_i.$$

Assigning the most probable values of parameter n in the first case, we calculate $\sum \omega^n$. Then we construct a relationship between these values and the flood volumes. As the calculated value, parameter n and, correspondingly, A are used. These provide the /16 best results. It is technically somewhat more convenient to use formula (14). We calculate their volumes for each flood, as well as $\sum \omega$ and $\sum \omega^2$. We construct the relationship

$$\sum Q = f\left(\sum \omega, \sum \omega^2\right), \tag{17}$$

according to which we determine parameters a and b.

The second problem of the calculation (forecasts) of flows is calculating the flow according to the genetic formula

$$Q(t) = \int_{0}^{t=\tau_{max}} f(\tau)\, q_{t-\tau}\, d\tau \tag{18}$$

or

$$Q = a \int_{0}^{t=\tau_{max}} f(\tau)\, \omega\, dt + b \int_{0}^{t} f(\tau)\, \omega^2\, dt. \tag{19}$$

The following formulas for calculating the lag curves are usually the most commonly used ones.

$$f(\tau) = \frac{1}{\tau (n-1)} \left(\frac{1}{\tau}\right)^{n-1} l^{-\frac{t}{\tau}}; \tag{20}$$

$$f(\tau) = a_1 \sin \frac{\pi\tau}{\tau_{max}} + b_1 \sin \frac{2\pi\tau}{\tau_{max}}. \tag{21}$$

Substituting calculated values of q in formula (18), we can easily determine the lag curve and calculate the water flows using methods already well developed in hydrology, specifically by employing specialized modeling devices. The problem of forecasting flow from unstudied basins pertains to establishing parameters n and τ of relationship $q = \psi(\dot{\omega})$, based on summarizing the results of observations of a number of studied basins and subsequent transfer of these relationships to the unknown ones.

It should be noted that in many regions of a zone of excessive moisture, in which the soils have a high infiltrative capacity, there are very specific characteristics of the formation of the surface layer. Under these conditions, the flow usually forms after the downflow of subterranean waters to the bottom surface and their filling of the microdepressions. For such conditions, it seems possible to make a simple but accurate solution of the problem of forecasting (calculating) floods.

Actually, the flow here after deducting small losses to evaporation during rainfall is numerically equal to flow from the territories covered by water

$$y = \omega i_x,$$

while the flow coefficient

$$\eta = \frac{\omega}{\omega_{tot}} i_x,$$

/17

where y — flow layer per unit time; i_x — intensity of rainfall; ω, ω_{tot} — respectively, area covered by water and total area of water reservoir.

DETERMINING AND FORECASTING SURFACE FLOW ACCORDING TO THE MIRROR AREA OF THE CHANNEL NETWORK

More than 90-95% of the entire flow is formed as the result of its sequential passage through the gulley-marsh area and river network to the main river. The value of the flow into the channels of main and large rivers directly from their slopes is so small that it can be ignored. Therefore, if we have certain controlling regions that permit us to determine the flows before the passage of flow from the gulleys into the river network, we could calculate the flow of the latter in a timely fashion corresponding to the lag time from the mouths of the gulleys to the closed river section. However, direct determination of water flows in these tributaries causes great difficulties. Therefore, it is expedient to determine the mean value of these tributaries over a certain length of their course prior to their entry into the subsequent tributaries. It is known that a nearly identical relationship exists between the mean width of each of these tributaries and its individual flow rate. This provides us with the prerequisites for calculating the total flow rate of tributaries of the examined category and to consider the relationship justified

$$q=f(\overline{B}_1, \overline{B}_2, \ldots, \overline{B}_n), \tag{22}$$

where q — flow rate of water of the examined category of tributaries; $\overline{B}_1, \overline{B}_2, \ldots, \overline{B}_n$ — respectively, the mean widths at a certain length of the isolated tributaries.

On the other hand, as is known, flow rate in a closed river section can be expressed by the formula

$$Q(t)=\int_0^t q_{t-\tau}\, p(\tau)\, d\tau. \tag{23}$$

Here $q_{(t-\tau)}$ — summed flow rates of water of tributaries of the examined category; $p(\tau)$— lag curve of water from the examined tributaries to the closed river section.

Hence, the problem pertains to revealing functions $q(\overline{B}_1, \overline{B}_2 \ldots, \overline{B}_n)$, to determining the lag curve, and to subsequent integration of the obtained relationships. The most complex problem is determining $q(\overline{B}_1, \overline{B}_2, \ldots, \overline{B}_n)$.

Knowing the hydromorphometric relationship whose study in hydrology is given significant attention can be of significant aid in discovering the latter function.

Thus, according to Velikanov: /18

$$\overline{B}=5{,}6\left(\frac{Q}{\sqrt{qi}}\right)^{2/5} \tag{24}$$

According to S. I. Rybkin, who processed a large amount of observation materials, we have

$$\overline{B}=6{,}75Q^{-0{,}57}k^{0{,}13}i^{-0{,}07}. \tag{25}$$

In these formulas, q is the flow rate of tributary water; i - incline $\left(k=\frac{Q_i}{Q}\right)$

In the general form for any region, the flow rate of water of tributaries can be approximated in the form

$$q = A\overline{B}^{n}, \tag{26}$$

where the exponent in the first approximation is $n \approx 2$, which in case of necessity should be verified. Then the influx of water can be determined according to the relationship

$$q = A \sum \overline{B}^{2}, \tag{27}$$

or

$$q = A \sum \overline{B}^{n}; \tag{28}$$

substituting in (23), we obtain

$$Q(t) = A \int_{0}^{t} \sum \overline{B}^{2}_{t-\tau} p(\tau)\, d\tau, \tag{29}$$

or

$$Q(t) = A \int_{0}^{t} \sum \overline{B}^{n}_{t-\tau} p(\tau)\, d\tau. \tag{30}$$

In a case in which the inclines of the examined tributaries fluctuate within wide limits, calculation is performed similarly to that presented, replacing (26) by the relationship $q = A \sum \overline{B^{n} \cdot i^{m}}$.

First, we verify the possibility of calculations according to formula (29) by ordinary methods, and in case of necessity we employ a correction by selecting parameters that best correspond to the initial data concerning flow according to formula (30).

Extremely significant in such an approach is the fact that the suggested method can now be verified, with an estimate of its accuracy according to the available materials of observations.

Actually, if we examine a basin with a very dense network of hydrometric stations, then according to the existing water conditions and their relationship with river width, we can determine $\sum \overline{B^2}$ and $\sum \overline{B^n}$. Having $\sum \overline{B^2}(t)$ and $\sum \overline{B^n}(t)$ as an input /19 function, and the water flow rate Q(t) as a discharge function, and using special modeling devices (specifically the PR-27, PR-43 and PR-49), one can calculate the lag curve and estimate the accuracy of forecasts.

Data on the length and amount of temporary water flows formed during the formation of floods can become an extremely interesting, important, and new indicator suitable for remote interpretation. Investigation of the dynamics of the temporary river network is an independently interesting problem.

On the other hand, in connection with the fact that the total extent of water flow $\sum l$ formed on the surface of a basin is a function of influx $\sum l = \psi(q)$, this total characteristic can also be used for forecasting flow from the basin. The advantageous use of this characteristic is due to the fact that linear objects are more easily and accurately interpreted on photographs of any particular scale. Today, however, investigations are unknown that reveal the structure of the relationship between the influx of water from a long, temporary river network.

In the final analysis, we can have $\sum l(t)$ as an input function, and the flow rate of water in the closed river section Q(t) as a discharge function.

Then the problem of forecasting flow pertains to determining

$$Q(t) = \int_0^t \varphi(\sum l)_{t-\tau} p(\tau)\, d\tau. \tag{31}$$

The use of changes not only in the temporary water flows, but also in the picture of the river network (its length), for estimating flow is extremely promising, since — proportional to the increase in the amount of water carried — the extention of regions of the river that were caught in the photographs (with other conditions being equal) should significantly increase. Therefore, the indicated properties of the river network can be useful for estimating the amount of water. Specifically, it should be noted that, even following the passing of floods, maximum overflows and the flows corresponding to them can be established according to the darkening of the river valleys.

DETERMINING CHANNEL RESERVES AND FORECASTING FLOW VOLUME ACCORDING TO THE MIRROR AREA OF THE RIVER NETWORK

The method of forecasting according to channel reserves is presently well developed [12, 28]. However, during its practical application, a number of difficulties are encountered that are due both to the inadequate amount of materials on the morphometry of channels, and to the comparatively scattered network of weather stations available for solving this problem.

After a rainfall, the volume of water in the small river network first increases, then the amount of water in the moderate sized and large river networks. After a certain comparatively /20 short period of time, the basic mass of water is concentrated in the large river network, and partly in the medium river network. Using observations from satellites or aircraft, one can determine the dynamics of the area of the water mirror of small $\omega_1(t)$, medium $\omega_2(t)$, and large $\omega_3(t)$ rivers.

There is a very intimate relationship between volumes of water W and the mirror area of water. Further, we know that water flow $\sum Q$ over a time near the period of emptying of all or the examined part of the river network, and corresponding to the period of early forecasts τ, is determined basically by the channel reserves.

Actually

$$\sum_0^t Q = W_0 + \sum q, \tag{32}$$

where W_0 — initial reserve of water in the river network; $\sum q$ additional flow through the closed river section from the last rainfalls. Reserves of water are determined:

$$W_0 = \sum_0^t Q - \sum q.$$

Having excluded the additional influx by the usual hydrological methods, we obtain a series of values for W_0. Thence, for periods of time when water is basically located in the large and medium channel network, we construct the relationship

$$W_0 = f\left(\omega_3, \frac{\omega_2}{\omega_3}\right). \tag{33}$$

We note that, in connection with the significant correlative relationship ω_3 and ω_2, the form of the relationship presented above is more convenient than W_0 (ω_3, ω_2).

For periods of time when a significant part of the water is in the channels of small rivers (ω_1) we construct a calculated relationship in the form

$$W_0 = f(W_{0\,\mathrm{cal}}, \omega_1). \tag{34}$$

Here $W_{0\ \mathrm{cal}}$ is calculated according to the relationship (33).

The transition to systematic information on areas of the water mirror of different categories of rivers creates the prerequisites for verification of forecasts of flow volumes.

It should be noted that, since the relationship may not strongly differ from a linear relation between the mirror area and volume of water in many cases, one obtains a simpler relationship $W = f(\sum \omega)$ and $\sum Q = \varphi(\sum \omega)$, where $\sum \omega$ is the total area of rivers of all categories. Calculation of the additional influx $\sum q$ is carried out by conventional methods.

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FORECASTING AND CALCULATING THE SUBTERRANEAN FLOW BASED ON ANALYSIS OF THE DYNAMICS OF BASIN WATER COVERAGE AND SOIL MOISTURE

When precipitation falls for a long period of time, the flow rate of water running from the soil columns into the water-bearing strata, according to the theoretical generalizations [18], has the form reflected in Figure 6. On the other hand, in the absence of an influx of water into the water-bearing strata, the level of subterranean waters, and consequently, the subterranean flow decreases according to an exponential law (Figure 7).

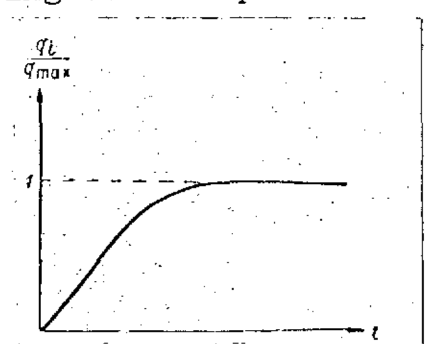

Figure 6. Change in time of influx of water q to the water bearing strata in fractions of maximum inflow q_{max} with constant basin moisture.

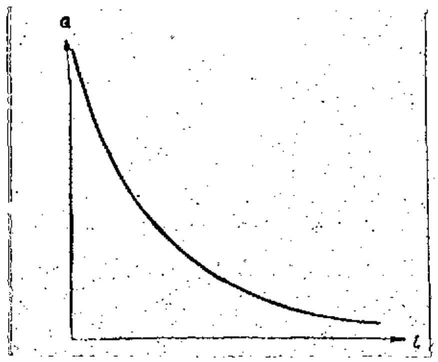

Figure 7. Curve of the subterranean flow decrease.

The amount of water flowing into the water-bearing stratum is

$$q = \mu \frac{dH}{dt} + \mu \frac{dH_1}{dt}. \qquad (35)$$

Here q is the influx of water over time dt; dH — increment in water-bearing stratum over time dt; dH_1— increment in water level calculated according to the decrease curve; μ— empirical coefficient representing a change in the amount of water in pores with fluctuation of the free surface relative to the volume of soil. In sandy soils, μ = 0.1 —0.15; in clay, μ = 0.01 — 0.10.

The flow rate of water in springs hydraulically unrelated to the level of the river is a function of the level of subterranean water. Actually, for a case in which one can ignore evaporation of subterranean water, its flow rate in the absence of inflow to the water-bearing strata can be expressed by the relationship / 22

$$\frac{dW}{dt} = \mu \frac{dH_1}{dt} = Q, \qquad (36)$$

where Q is the flow rate of spring water per unit area of the water bearing stratum fed by this spring; W — variable reserve of water in the water bearing strata.

The problem in the period of replenishment of stores of subterranean water is somewhat more complicated to solve. Usually, over the examined short period of time of supplying the water-bearing stratum, the positive value of the level change is so small that it can be ignored, when compared with the depth of the water-bearing stratum, and therefore does not significantly alter the dynamic characteristics of the flow. In connection with this, the average flow rate of spring water over the time of the investigated level increase can be considered along a typical diminishing curve that is continually transformed as the result of influx of water and subterranean flow according to the diagram shown in Figure 8.

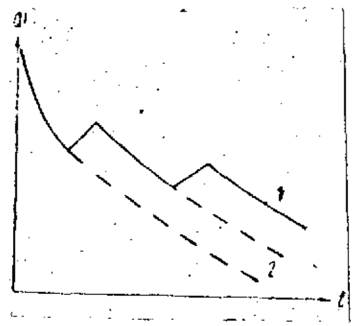

Figure 8. Effect of influx of water into the water bearing strata on transformation of the curve of subterranean flow decrease.

1- transformed decrease curve; 2- decrease curve without taking transformation into account.

If the influx of water q is known, then using the balance method and the curve of spring flow rate decrease, one can also calculate the water flow rate of a spring according to the volume curve. Actually, the volume of water of the water-bearing stratum feeding the spring — above which the water level corresponds to a certain arbitrarily chosen lowest possible water flow rate — is

$$W - W_{\min} = \int_{Q_{\min}}^{Q} Q(t)\,dt; \qquad (37)$$

Here $\int_{Q_{\min}}^{Q} Q(t)\,dt$ is the area limited by the decrease curve (see Figure 7) in an interval Q and Q_{min}.

Knowing the flow rates of water and the corresponding volume $(W-W_{min})$ one can calculate the curve of volumes $W-W_{min} = f(Q)$.

By conducting calculations over short intervals of time, one can determine the flowing volumes of water and the flow rates of water corresponding to them, since the decrease curve $Q_t = f(Q_{ini})$ can be easily transformed into curve $Q_t = f(W_t)$ or $Q_1 = f(W-W_{min})$.

The necessary volumes of water for such calculations are obtained according to the formula /23

$$W_{t+\Delta t} = W_t + (\bar{q} - \bar{Q}_t)\Delta t, \qquad (38)$$

Here $W_{t+\Delta t}$, W_t are the volumes of water at time t and $t+\Delta t$; $\bar{q}$ and $\bar{Q}$ are influx of water into the water bearing strata and flow rate of a spring over time Δt according to the decrease curve.

Calculations of the subterranean flow are complicated by the necessity of calculating its reaction with the surface flow and calculating the time of flow of subterranean waters along the channel network. However, here, too, we have certain facts that facilitate the calculation.

Actually, as was shown in the investigations of B. I. Kudelin [18], in the course of a flood or overflow, the period of withdrawal can be terminated, as can the period of replenishment of the subterranean flow, and, with respect to their magnitudes, these two values are quite close (Figure 9).

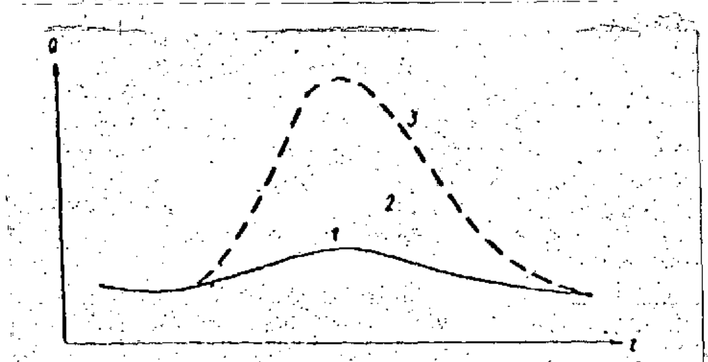

Figure 9. Relationship of surface and subterranean waters.

1 - Subterranean flow in the absence of its interaction with surface waters;
2 - Change in the subterranean flow resulting from its reaction with the surface flow;
3 - Surface flow

Therefore, it seems expedient to calculate that subterranean flow as would exist in the absence of the perturbating effect of floods, considering the role of the latter as an independent problem.

With respect to the lag time, one can determine it by employing isochrone methods, lag curve methods, etc., which are well developed in hydrology. Moreover, by taking into account the much smaller changeability of the subterranean river flow, when compared with the surface flow, in a number of cases one can consider subterranean flow equal to the mean value of influx into the river network over the time of channel lag, without large errors.

In principle, one can use the same approach as was used for the surface flow for calculating the subterranean flow, i.e., calculations are carried out according to the Dyuamel formula

$$Q(t) = \int_0^{t=\tau_{max}} q_{t-\tau}\, p(\tau)\, d\tau. \qquad (39)$$

Here, the lag curve $p(\tau)$ can be examined, based on an analysis of a combination of the decrease curves of the subterranean flow and the lag curve in the channel network. For a simpler solution /24

$$Q(t) = \int_0^{t=\tau_{max}} \bar{q}_{t-\tau}\, p_1(\tau)\, d\tau. \qquad (40)$$

Here $\bar{q}_{t-\tau}$ — influx into the water-bearing strata of channel lag τ averaged over time; $p_1(\tau)$— lag curve calculated according to the curve of subterranean flow decrease.

The examined approaches have the advantage that they reveal the origin of the subterranean flow, since they demonstrate which fractions of the flow it consists with respect to the time of its formation. However, the practical application of this method is made difficult by the fact that calculations according to the lag curve have to be carried out over a long period. We note that the influx of subterranean water $\bar{q}$ can be calculated in principle according to the actual course of the subterranean flow from an equation that is written in the form

$$\bar{q}_{in} = \frac{W_{t+\Delta t} - W_t}{\Delta t} + \bar{Q}_t. \qquad (41)$$

It was shown above that in the final analysis, calculating and forecasting the regime of subterranean waters are primarily related to the necessity of determining the source of subterranean waters. In their turn, all processes of replenishing the reserves of subterranean waters that pass through the surface of the Earth occur during the accumulation of water on the surface of the basin, whose basic characteristic could be the course of basin water coverage in time. Another important characteristic could be soil moisture, since the rate at which water passes through into the underlying ground is directly related to it. These characteristics can be estimated using photographs of the Earth's surface. Hence, a further problem consists in directly predicting the subterranean water regime according to such photographs.

One of the prerequisites in solving the problem of predicting surface and subterranean flow examined earlier was striving to avoid characteristics that are difficult to generalize — for example, the distribution of coefficients of filtration, the hydraulic-morphometric characteristics of basins, channels and strata, etc. This is successfully done by introducing such integral characteristics of flow processes as decrease curves, lag curves, etc., that are determined according to the data of observations and by means of calculations. We note that the suggested approaches can prove extremely effective in reclamation hydrology and hydrogeology. As is known, it is important to calculate the surface flow, the subterranean feed, and level of subterranean waters for establishing the irrigation norms. Together with this, the extreme multiplicity of irrigation ditches and the degree of their coverage under different conditions of irrigation do not make it possible to obtain any suitable solution to these problems. Introducing areas of water coverage of the irrigated territory into the calculation makes it possible to obtain a more accurate solution, for this area is intimately linked with the values of surface flow and subterranean feed.

INITIAL MATERIALS FOR PRACTICAL USE OF THE SUGGESTED METHODS OF FORECASTING AND CALCULATION

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The initial materials can be divided into three groups: terrestrial, aerial, and satellite.

Terrestrial materials include the data on flow observations in closed sections; water levels; topographic materials that characterize the area of water surface in channels and on the surface of a basin, as well as terrain relief, soil relief and plant cover; curves of the relationship of channel area with water levels; soil moisture, etc. Part of these characteristics can be obtained from low flying aircraft or by means of photographs taken from observation towers.

These materials can be used for several purposes, namely:

1) For developing a method of forecasting and calculating in certain basins and flow stations and for establishing the effect of accuracy of elements measured on the error of the forecasts;

2) For clarifying the relationships necessary in using remote measurements, for example, establishing the type of relationship between the area of large accumulations of water on the surface of a basin and the total area of basin water coverage under different physico-geographic conditions;

3) For determining the effect of physico-geographic characteristics of the basins on the relationship between the measured flow factors and values of the latter for developing a method of shifting from studied basins to unstudied basins;

4) Using these materials for interpreting photographs taken from satellites and high altitude aircraft;

5) For compiling certain types of forecasts, and particularly, of catastrophic floods, (for example, erosive floods).

The resolving capacity of the aerial apparatus fluctuates within an extremely broad range — from 50 to 12,500 m [29]. The scale of a photograph m, as a rule, is primarily determined by the photography altitude H and by the focal distance of the camera f. If one does not take into account the angle of inclination of the photograph and the curve of the Earth, then $\frac{1}{m} = \frac{f}{H}$. For the examined purposes, primary significance lies in satellites with low orbits and partially moderate orbits, which can provide high accuracy of observations of the small objects examined above.

The resolving capacity of the MSS multispectral scanning system and the RBV television system of the ERTS-1 satellite at 6000 scanning lines approaches the resolution obtained by manned spacecraft from lower altitudes.

One of the most complex problems of obtaining reliable aerospace photographs at any time is excluding the effect of cloud cover and plant cover.* Extremely promising for excluding the effect of cloud cover are investigations of measurements carried out in the radio range (centimeter range). During investigations in the radio range, the Earth's surface should either radiate radio waves set up in a generator system or record the terrestrial eigen radiation or atmospheric radiation (passive systems). And in certain cases, it can be expedient additionally to use low-flying aircraft and helicopters, besides satellites, specifically during catastrophic floods for excluding the effect of cloud cover. On the whole, we also note the extremely great promise of using low flying aircraft and helicopters for developing methods of forecasting. It should also be noted that the actual solutions will depend on the brightness details of land mass elements and the transmission function of the atmosphere. /26

For bright elements of the land mass, and linear objects (a river, a lake), these can be significantly higher, which is particularly important for hydrology.

As B. V. Vinogradov and A. A. Grigor'yev [7] note, in the photographs taken by the long focus cameras from "Gemini-4" (M 1:700,000), all of the gulley-marsh network depicted on the map of the State of Mexico (M 1:200,000) appeared in detail. In the Arabian desert, the multiple-branched erosion network was isolated well on photographs taken by this satellite as fine, light threads.

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* In the near future, it will be hardly possible to obtain photographs along forest covers. In most regions covered by forest, however, there are also areas that are free of forest cover. Probably, the flow from such areas will be an indicator of the flow from the surrounding wooded territories as well. This would make it possible to note the most simple solution based on experimental studies — establishing transfer functions from these indicators to flow from the wooded territories surrounding them.

Table 1 provides a range of characteristic values of the hydrological characteristics that require remote measurements for the use of suggested forecasting methods in accordance with the physico-geographic characteristics of the basin and the method of forecasting.

For making the optimum decision (of course, in cases when human life is not in question), we should be governed by the condition that the difference between economy as the results of forecast (E) and expenditures (Ex) in conducting measurements and comparing forecasts will be maximum ψ (Δ) = max. For this purpose, it is necessary to construct a relationship between possible economy (E) and the prediction error Δ, as well as the degree of total expenditures for the forecast and its error. /27

TABLE I.

Measured characteristic	Range of characteristic dimensions
Fraction of basin area covered by water	1,000 - 30,000 km^2 (basin).
Areas of wetting	1,000 - 30,000 km^2 (basin).
Areas of separate microlakes	From several square meters to several square kilometers
Width of water mirror of the gulley-marsh network	10 - 30 m.
Area of water mirror of the river system	Length of rivers: 10 - 300 km. Width of rivers: 50-3000 m.
Length of temporary water flows	1 - 3 km.

In solving equality $E(\Delta) - Ex(\Delta) = \psi(\Delta)$, we determine $\psi(\Delta)$ = max.

In such an approach, determining the optimum relationship between terrestrial, aerial, and satellite measurements, as well as revealing the rational proportions between route, selected, and large scale photoimages of the terristrial surface will be extremely important.

THE USE OF REMOTE SOUNDING FOR FLOW FORECASTS IN THE USA

Studies are today being carried out in the USA [35,37] on creating a computer system for producing hydrographs of flow from water reservoirs which have not been studied in a hydrological respect, involving the results of remote measurements, specifically satellite measurement, in addition to the conventional data.

At the basis of this project lies the hypothesis that an intimate relationship can be established between the parameters of a model that describes the formation of the rain flow and the physico-geographic characteristics of the water reservoir, determined by the aid of remote measurements.

The project consists of three parts:

1. Developing and testing mathematical models of a flow whose parameters are found according to the data of remote measurements, for example, aerial photographs, and certain auxiliary terrestrial observations, for example, data on soil moisture, based on observations of a well studied region. The Tennessee river valley could be chosen as such a reference region, for this valley has a dense network of hydrometeorological stations.

2. Conducting studies for any other basin with a thick network of hydrometeorological stations, which differs noticeably from the Tennessee river valley in its physico-geographic and climatic conditions.

3. Testing the developed model in the absence of flow observations for the water located in different parts of the globe.

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Work on the first part of the project is supposed to be completed in 1973.

At the basis of the investigations lies the known Stanford model that makes it possible to produce the elementary flow formation processes (infiltration, surface lag, transformation of the flow hydrograph, etc.), and to calculate the flow hydrograph on the basis of observations of precipitation and evaporation. The parameters of the model (there are 13 of them) are found by methods of optimization according to observations of the hydro-meteorological factors, and flow measurements in the closed section of the water reservoir. In all, 35 water reservoirs in the Tennessee river valley are planned for consideration. Observations of 25 of the water reservoirs will be used for determining the parameters and constructing the correlationships of these parameters with the physico-geographic and topographic characteristics of the water reservoirs. Observations of 10 of the water reservoirs will be used as material for checking these relationships.

An interesting study in a theoretical and practical regard was carried out according to the developed models for specific water reservoirs — estimating the sensitivity of the calculated hydrograph to errors in the assigned parameters. These estimates made it possible to establish the preliminary accuracy requirements of measuring the initial values that are cited in Table 2.

The basic task is the problem of identifying the characteristics of the water reservoir according to the aerial and satellite photographs. Here, panchromatic color, infrared, multispectral, or other photographs, soil maps, topographic and geological maps, and geographic descriptions will be used. It is

TABLE II

Studied characteristics	Required resolution (m)	Type of observations
Basin topography	30	High altitude aircraft
River network	15	High altitude aircraft
Types and distribution of plant cover	90	Low orbiting satellites
Soil types	30	High altitude aircraft
Infiltration parameters	-	Ground observations
Topography and properties of river valley	3	Ground observations or low flying aircraft
Precipitation	-	Ground observations
Evaporation	-	Ground observations

assumed that it will be possible to carry out continuous remote observations of the water reservoir as the result of carrying out the project, and that on the basis of these observations, by the aid of a computer, it will be possible to process the data of remote terrestrial observations and make forecasts of rain floods.

While highly evaluating the technological aspects of the project, one can, however, foresee that the accuracy of forecasts made according to this project will not be high, on the basis of a great deal of experience in hydrological investigations, since the correlation relationships with such short series (25-35 water reservoirs) and such a large number of parameters cannot be /29 reliable. We note that here one can expect the best results from the empirical relationships already accumulated in hydrology that are based on incomparably greater observation material.

This project does not contain possibilities for improving the quality of forecasts in the basins studied, since the basic problem (flow loss) is solved by means of a traditional method.

When supplementing these studies with new theoretical constructions and using the new information for developing more accurate methods of calculating flow loss, determining the influx of water and the volume of channel reserves, in the future one can expect to create the prerequisites for a significant improvement in forecast quality.

STUDYING THE SNOW COVER AND FORECASTING SPRING HIGH WATER BY A REMOTE METHOD *

Today, data from aerial photography and television images from satellites are effectively employed, in addition to terrestrial observations for determining the characteristics of the snow cover: the height of the snow line in mountains [30], and the area of basin snow cover [30, 35, 38, 39, 40].

The first manuals on employing satellite photography for mapping the snow cover are beginning to be published [38].

The height of the snow line directly enters certain of the forecasting relationships, and therefore, its remote determination can prove extremely useful for improving forecasts of mountain river flow.

* In order to avoid excessive discussions, formation of the spring flow is viewed from traditional positions — an analysis of the effect of melting snow on the melted snow flow. During the examination of the direct cause of accumulation of melted snow waters on the surface of the basin, in another unaccustomed plane of measurements we encountered a number of unstudied processes. This includes the formation of the primary rivulet network, the numberless accumulations of water before the snow accumulations, breaks in snow "dams", etc. For creating a new theory, a great deal of theoretical and experimental studies are required.

With respect to the area of basin surface coverage by snow, these data, and particularly the data of aerial photography, can also be useful for calculating the hydrograph of the melt flow. Actually,

$$Q_t = \int_0^{t=\tau_{max}} \eta F_{t-\tau} i_{t-\tau} p(\tau)\, d\tau, \qquad (42)$$

where i — rate of water release of the snow cover; F — basin area covered by snow; p(τ) — lag curve; η— coefficient of flow depending upon soil moisture (w), depth of freezing (H), layer of melting snow (x_t) /30

$$x_t = \int_0^t i\, dt.$$

The flow coefficient can be determined according to the empirical data

$$\eta = f(x_t, w, H).$$

The rate of water release in the formula can be calculated according to ground observations by the thermal balance method or, more approximately, according to air temperature.

Soil moisture w can be determined according to remote measurements in a period of time preceding the date of snow cover formation.

The depth of freezing can be obtained according to the data of agrometeorological observations. Hence, it is possible to compile a forecast of the spring flow based on a combination of remote and terrestrial observations.

Together with this, the possibility of determining reserves of water in the snow cover is not excluded, based only on data of areas of basin snow coverage and principles of snow melting. Here, two cases are possible: the first — investigation of a picture of snow drifting over a small territory by photograph details; the second — an investigation in which the resolving detail characteristics of the photographs are not great, and data on the areas of coverage of the surface of the entire basin are examined. The latter is still not so great that differences in the thermal regime, that determine snow melting, are significant.

In the first case, one can obtain the following data:

1) A change in time of the fraction of basin area covered by snow $\frac{F_{sn}}{F_{tot}} \% = f(t)$; in the period of snow melting;

2) A change in time of the total layer of melted snow (in the change to water), calculated according to ground meteorological data (for conditions of heavy cover, using methods well known in hydrology);

3) The integral curves of distribution of snow reserves $H_i = f(\bar{H}, p)$, which, in the opinion of V. D. Komarov, are stable in time and can be obtained according to the materials of previous observations (Figure 10). In this case, p — is the probability of exceeding the assigned value of standing snow reserves (H_i).

In its turn, the relationship which changes in the period of snow melting $\frac{F_{sn}}{F_{tot}} \% = p$:

$$p = \frac{F_{sn}}{F_{tot}} \%.$$

The horizontal lines in Figure 10 correspond to the H_1 calculated according to the terrestrial data on layers of melting snow. Knowing H_i obtained according to the terrestrial data and $\frac{F_{sn}}{F_{tot}}$ %, obtained by means of remote measurement, it is not difficult to calculate the mean reserve of water in a snow cover $\bar{H}$ according to Figure 10: /31

$$\bar{H}=\varphi\left(H_i, \frac{F_{sn}}{F_{tot}} \%\right). \quad (43)$$

Hence, at different moments in time we are able to determine reserves of water in the snow cover using the indicated method, which makes it possible continuously to control the calculation.

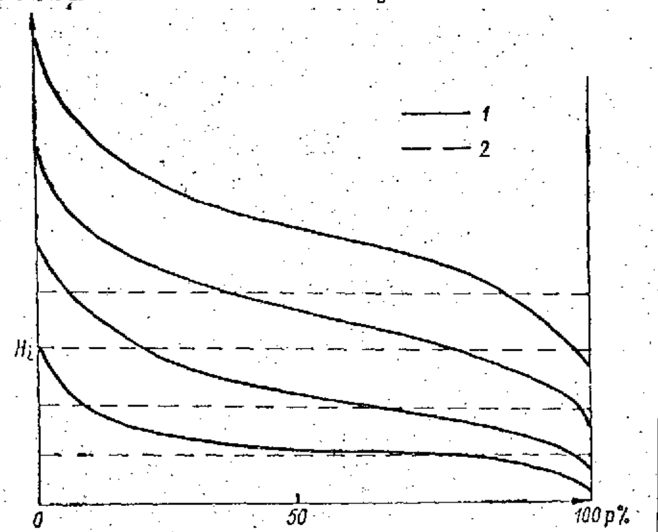

Figure 10. Integral curves of the distribution of snow reserves (H) over the area of a basin expressed in % (p%).

1- integral curves of snow reserves; 2- layer of melted snow.

The possibility of applying such an approach to estimating the snow reserves is confirmed in the investigations of V. D. Komarov [14], who demonstrated that the values $\frac{F_{sn}}{F_{tot}}$ % obtained by calculation (according to the value of snow melting and the integral curve of snow reserve distribution) almost completely coincide with those determined according to the data of terrestrial observations. /32

The possibility of solving such a problem for the above mentioned second case is less clear. Actually, for this case, we should consider the integral distributions of mean values of snow reserves over different territories, due to the fewer details. It is therefore necessary to clarify the effect of territory dimensions on the shape and stability of these distribution curves, and only after this can one employ a method of calculation that is significantly analogous to that described above.

The possibility of estimating snow reserves according to natural gamma-radiation is also extremely interesting. Actually, soils and mountains contain natural radioactive elements that emit gamma-quanta (the elements uranium, thorium, and the radioactive isotope of potassium, potassium-40). Up to an altitude of several hundred meters, the gamma field is caused by these sources of gamma radiation. In passing through the snow cover, the intense gamma radiation diminishes according to an exponential law, depending on the reserves of water in the snow cover.

This method of measuring reserves of water in the snow cover was developed by Soviet scientists [24, 27, 22], and then began to be employed and underwent a certain amount of development in the work of foreign scientists [41].

Based on the data of the aerial gamma-survey carried out from altitudes ranging from 25 to 100 meters, it proved possible to characterize the distribution of water reserves in the snow cover with an accuracy near that of the ground data [27, 22].

According to the known values of water reserves in the snow cover x, determined by this remote method, one can compile a long term forecast of the spring flow. Actually, the total layer of spring flow y is approximately expressed by the equations:

$$y = x - p_0\left(1 - e^{-\frac{x}{p_0}}\right), \tag{44}$$

or

$$y = x - p_0 \operatorname{th} \frac{x}{p_0}. \tag{45}$$

The physical significance of parameter p_0 lies in the fact that it is equal to the maximum possible basin water absorption. For regions with deep soil freezing, this parameter depends only on soil moisture.

The characteristics of soil moisture can be determined by satellite or aerial photography. The calculated relationship is compiled according to the materials of previous observations.

Since soil moisture usually changes little over the course of the winter, this value or index that characterizes it is taken to be equal to soil moisture that has been observed in a period immediately preceding the date of establishing the stable snow cover. With a slight depth of freezing, which is frequently observed in regions with an unstable winter, one introduces corrections for weak soil freezing. It is interesting to note that for quite extensive regions one can construct territorially common relationships that enable one to compile a forecast of the flow volume for rivers for which observations are not available, as was established by the investigations of V. D. Komarov [14].

With respect to forecasting maximum flow rates of water in the spring flow period, this must be based on forecasting the total volume of the spring flow, as is usual. /33

This method has proven extremely promising in calculating reserves of water on the surface of a basin in the upper layer of the soil as well [23, 24, 32]. Inasmuch as the accumulation of water on the surface of the basin and the moisture of the sub-surface layer of the soil to a depth on the order of 30 cm also exert an effect on diminishing gamma-radiation, a change in the radiation intensity can be determined by the moisture reserves in the upper level of the basin, which is of decisive significance in forming the surface and subterranean flow.

It is expedient to organize systematic stationary observations of the natural gamma-field simultaneously with the existing complex of hydrological observations. This can reveal new capacities for studying and forecasting hydrological processes.

SOME FUTURE PROBLEMS OF INVESTIGATING PROCESSES OF FLOW FORMATION USING AEROSPACE PHOTOGRAPHY

One of the modern problems of hydrology is using information derived from photographs of the surface of the Earth for the purpose of analyzing hydrological processes.

The basic trends in solving this important problem are the following:

a) Developing a theoretical concept that permits one to analyze flow formation processes using new methods;

b) Carrying out a complex of terrestrial and high altitude observations of the process of flow formation both for improving the theory and for establishing the parameters of calculation models;

c) Establishing requirements permitting one to create a system of ground and high altitude observations that is optimum from an economic and hydrological point of view.

It has already become necessary to create an experimental station used for satellite investigations, as well as special hydrological stations with a significant program of experimental investigations, for the interests of hydrology. Such a station should include the following:

a) Basins of comparatively small rivers with detailed illumination of the topography of the surface and channel network and a system of observations making it possible to fix the level and flow rates of water, the thermal regime of water reservoirs and the dynamics of area of the channel networks;

b) Flow stations located under different physico-geographic conditions. Here, certain of these should have devices for irrigation. In addition to the conventional investigations, the possibility of carrying out surface photography from permanent towers, tethered weather balloons, and stationary measurement of gamma-radiation should be provided. These areas should be equipped with a detailed topographic base, as well as periodic photographs of reserves of water at different flow rates. /34

Besides being useful for special problems, the terrestrial observations can prove vital for standard interpreting of remote observations conducted over test areas from satellites and aircraft.

Besides being linked with satellite and aircraft experimental investigations, the above-mentioned stations should carry out a study of the structure of the flow necessary for developing a theory of its formation and for developing calculation and forecast models.

A number of the problems of hydrological forecasting formulated above can be solved only through the use of high resolution photographs, which unavoidably entails a large volume of information. Therefore, it is necessary to provide for solution of these problems based on standard methodological developments for typical homogeneous underlying surfaces at selected test regions, using images of both high and low resolution. During this process, the satellite photographs with low resolution should be used for revealing the homogeneous physico-geographic regions over which the interpretation indices obtained in the selected reference regions will extend.

The optimum system of test foundation regions for aerial and satellite high resolution photography, just as in determining the requirements (which are differentiated for different hydrological problems) for apparatus resolving capacity, will be determined by the results of combined subsatellite experiments.

In connection with solving a number of hydrological problems by remote methods, including fundamental problems of flow forecasting, it is vital to have improved remote sounding apparatus. On the one hand, such an improvement will take place by increasing its resolving capacity and, on the other, by employing new methods of photography in ranges that differ from the visible. The latter trend is primarily dictated by the fact that an important hydrological characteristic is the water reserves (whether it be water reserves of a closed reservoir, channel systems, the soil, snow cover, or the atmosphere), which are necessary both for water balance estimates, and for predicting the flows of rivers, and which are not directly determined according to photographs received in the visible range.

In this regard, measurement of the eigen thermal radiation in the centimeter range using methods of passive and active radar — for estimating the water reserves of the indicated hydrological objects — will bring significant progress in hydrology by obtaining new quantitative information.

Creation of the appropriate apparatus and the development of a method of quantitatively estimating water reserves of the snow cover, atmosphere, soil, and closed reservoirs, according to radiation in the centimeter range of the spectrum, is now an extremely pressing and immediate problem whose solution will open wide possibilities for employing remote methods in hydrology. /35

Moreover, measurements in the centimeter range, even with the existing low resolutions, can prove to be of great help in interpreting photographs in the visible range as supplementary information not subject to the effect of cloud cover.

Problems of studying the condition of reservoirs, of estimating their degree of contamination and biological productivity, as well as the character of the changes in a number of hydrological processes such as snow melting, can be solved by using multizone photography based on the principles of the spectral albedo of the water and snow surfaces in various states.

A no less important technical problem can be the development of methods of automatically processing images on the computer and similar methods for the purpose of recognizing, isolating, generalizing, and classifying hydrological objects and phenomena, and also for automating the process of obtaining numerical parameters that are so important for the hydrological forecast. The application of methods of automated image processing to hydrology is particularly important, inasmuch as the water reserves from all types of natural resources are the most changeable element.

The model of predicting hydrological characteristics examined earlier is extremely schematic and requires improvement. It seems, however, that such models can be useful for the following reasons:

1. These models include new factors not examined in preceding flow models.

2. The factors included in the examination (the area of basin water coverage, channel area, etc.) are directly related to characteristics of flow and make it possible to carry out the calculations, bypassing elements which are difficult to estimate such as flow loss and precipitation. Therefore, these methods contain within themselves the capacity of more accurate forecasting than the usually employed methods of flow forecast based on precipitation and flow loss.

3. The approaches to forecasting flow presented above stimulate the development of new experimental and theoretical investigations that directly connect the structure of the basin surface with the flow structure.

The hydrological prerequisites of forecasting flow according to photographs of the Earth's surface examined in this chapter indicate new possibilities in this region of knowledge that have appeared due to the development of remote methods of investigating natural resources. Certain of these possibilities can be realized in a comparatively short period of time. However, complete use of the new possibilities requires a detailed analysis of the accuracy of determining hydrological characteristics according to photographs made in various regions of the spectrum, in different scales, and under different weather conditions, with subsequent estimation of the effect of these factors on the accuracy of flow forecast.

Such an analysis must serve as the basis for establishing requirements for the accuracy of photographic interpretation, the accuracy of establishing transfer functions of the atmosphere and the development of new methods of studying the Earth's surface applicable to the examined problems. /36

In conclusion, it is vital to emphasize that the varied processes of flow formation and the clear sequence of their development in time in various scales create the prerequisites for developing a system of flow forecasting methods based on different scales in time and space of the phenomena that occur on the Earth's surface. This creates favorable conditions for a successive (proportional to the development of interpretation accuracy) application of remote methods of measurement for the purpose of studying the process of formation of the water-dry land regime and of flow forecasting.

Thus, during the development of extensive investigations, the possibility of creating a new system of forecasting almost all types of flow, and partly, methods of calculating flow based on remote sounding is appearing. It seems that this new system of forecasting flow will gradually supplement the existing system, and in certain cases — in which it proves more accurate and economically more advantageous — will replace it.

The basic significance of this study is that it leads to a clear program of future investigations both for the purpose of further learning about the process of flow formation, and developing methods of calculating flow that are based not only on measurement methods, but also on remote ones.

The problems examined here can also be useful in other branches of a rapidly developing science — aerospace methods of geography. A significant role in the formation of this science belongs to K. Ya. Kondrat'yev [8, 10, 15]. An important study in this field is also being carried out in the geography department of Moscow State University under the supervision of K. A. Salishchev [25].

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